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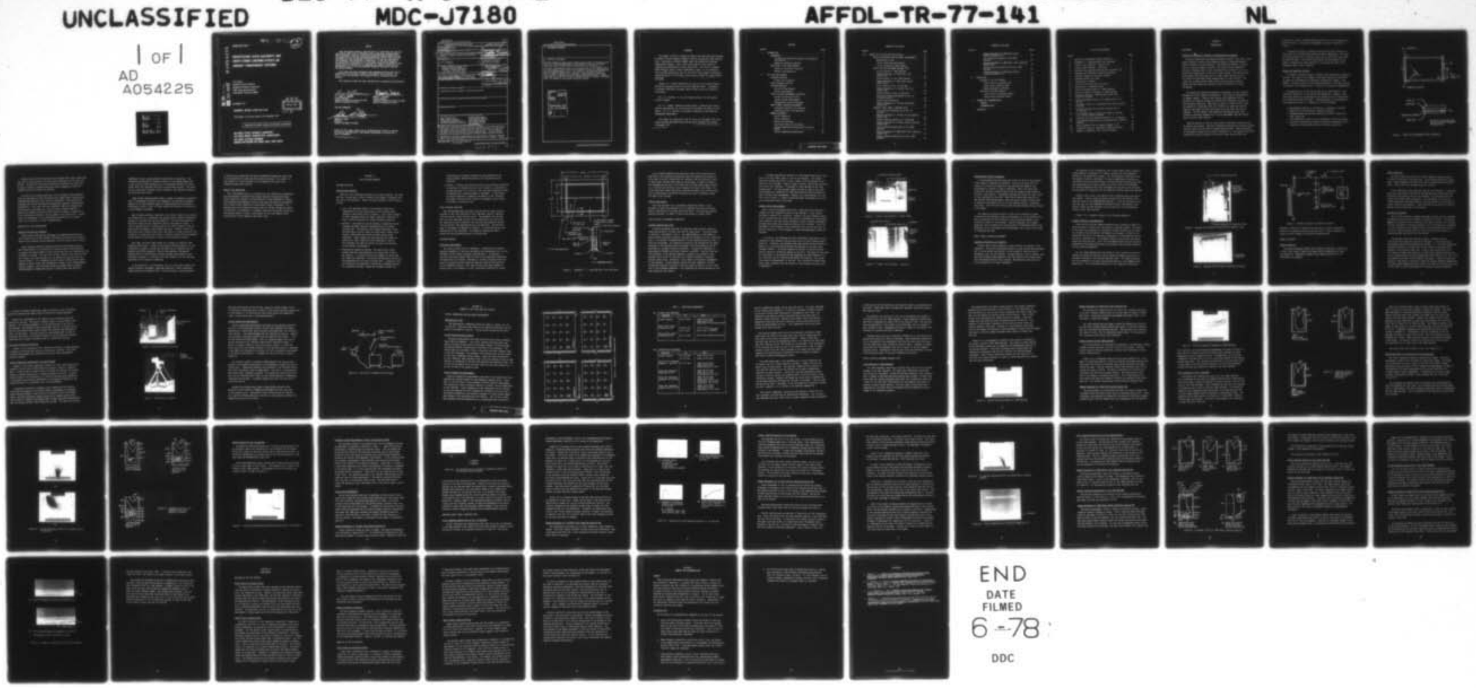

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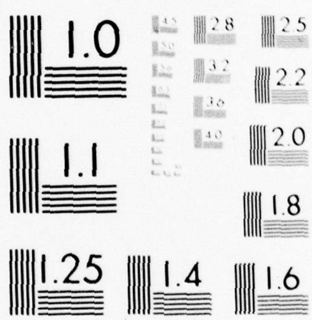

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PRECIPITATION STATIC ELECTRICITY AND SWEPT-STROKE LIGHTNING EFFECTS ON AIRCRAFT TRANSPARENCY COATINGS

R.C.Twomey
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DECEMBER 1977

TECHNICAL REPORT AFFDL-TR-77-141

Final Report For Period February 1977-December 1977

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Anti-Static Coatings
RCS Coatings

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Swept stroke lightning and static electric discharges on aircraft windshields and canopies will induce large electrical transient currents into the fragile transparent conductive coatings which are used for anti-icing, de-fogging, and radar cross section control of these transparencies. A test program was conducted to study possible detrimental effects of these transient currents.

Representative aircraft transparencies were subjected to laboratory simulated swept stroke lightning magnetic fields and static electric charging. Damage

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assessment methods included visual inspection with normal and polarized light, electrical resistance measurements of the conductive coating, and thermal inspection using a closed circuit infrared television technique.

The results indicated that swept stroke lightning with a high level re-strike will most probably cause a failure or instigate a failure in a heated coating during subsequent heating cycles. The tests also indicated that static electric induced transients in a moderately large transparency should not cause problems in coatings that are properly designed and applied. However, these same transients can initiate an ultimate failure if visible or invisible flaws, are present in the original conductive coating.

FOREWORD

This report is one of a series of reports that describes work performec by Douglas Aircraft Company, McDonnell Douglas Corporation, 3855 Lakewood Blvd., Long Beach, California 90846, under the Windshield Technology Demonstrator Program. This is the second report on the subject of lightning and precipitation static electricity. The first is document AFFDL-TR-76-75, which is fully identified as Item 1 in the references. This work was sponsored by the U.S. Air Force Flight Dynamics Laboratory, Wright-Patterson Air Force Base, under Contract F33615-75-C-3105, Project 2202/1926.

Captain D. C. Chapin (AFFDL/FEW) was the Air Force Project Manager during the conceptual phase of the work reported herein. Lieutenant L. G. Moosman (AFFDL/FEW) succeeded Captain Chapin during the conduct of the program.

Mr. J. H. Lawrence Jr., was the Program Director for the Douglas Aircraft Company.

Mr. R. C. Twomey, Radiating Systems Design, Lightning and P-Static, Avionics Engineering, was the Principal Investigator and author of this report. Mr. J. O. Suffron, Environmental Engineering, performed the Thermograph measurements.

This report was submitted to the Air Force on 10 December 1977, and covers the work performed during the period 27 February 1977 through 10 December 1977.

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LIST OF ILLUSTRATIONS

SECTION I

INTRODUCTION

BACKGROUND

The Roles of Conductive Coatings in Windshields and Canopies

Aircraft windshields and canopies frequently employ a very thin, transparent coating of electrically conductive material sandwiched between layers of plastic or glass material. The conductive coating is usually used as a heating element to maintain the outer surface temperature above the freezing point of water to prevent the buildup of ice, or to prevent the condensation of fog on the inner surface. For some military applications the coating may act as a radar signal reflector to aid in controlling the radar target characteristics of the aircraft. The latter use is known as RCS (radar cross section) control, and may employ the same conductive coating as used to provide anti-icing or de-fogging.

The conductive coatings are generally proprietary in their chemical makeup and in their method of manufacture. They have one characteristic in common, however. They are very fragile and, therefore, must be applied to an interior surface of the multi-ply windshield or canopy to gain physical protection. When they are used as a source of heat, they are applied to a relatively thin ply of plastic or glass which serves either as the outer ply (for anti-icing) or as the inner ply (for de-fogging). For RCS control, the coating can be applied to any inner surface as high heat conductivity is not a requirement when the coating does not serve a dual purpose.

When the coating is used as a heat source, electrical connections must be made to the coating. Electrical grounding connections to prevent internal sparking should also be made to unheated coating areas. (More information on the general subject can be found in Reference 1.) The external electrical connections are made by means of electrical buses located within the

windshield or canopy structure which make contact to the transparent conductive coating. A typical bus arrangement is shown in the sketch of Figure 1.

A conductive coating is sometimes applied to the outer surface of a glass outer ply to prevent the buildup of static electricity. This type of coating usually has a very high resistance to allow high light transmission efficiency. Anti-static coatings are not the subject of this report, although prior work (Reference 1) has shown that they can be damaged by swept stroke lightning.

<u>Damage to Conductive Coatings</u>

A frequent in-service problem is damage to the electrically conductive coating. The cause of this damage is not always known, but the results can mean the replacement of an expensive windshield or canopy. This damage is usually associated with heated windshields, since they comprise the majority of the applications of conductive coatings to transparencies.

The damage may be in the form of bubbling or discoloration in the conductive coating or in the interfacing laminations. Changes in the bus-to-bus electrical resistance may also negate the use of the coating as an effective electrical heater. Candidate causes or contributors to the damage may be one, or a combination, of the following:

- o Manufacturing defects in the coating or coating-bus interface.
- o Impurities in the laminate or conductive coating.
- o Inadequate edge sealing which permits the entry of moisture or other impurities.
- o Over-temperature caused by faulty temperature control equipment.
- o Electrical overstressing caused by external environments such as lightning or precipitation static (P-static) electricity.

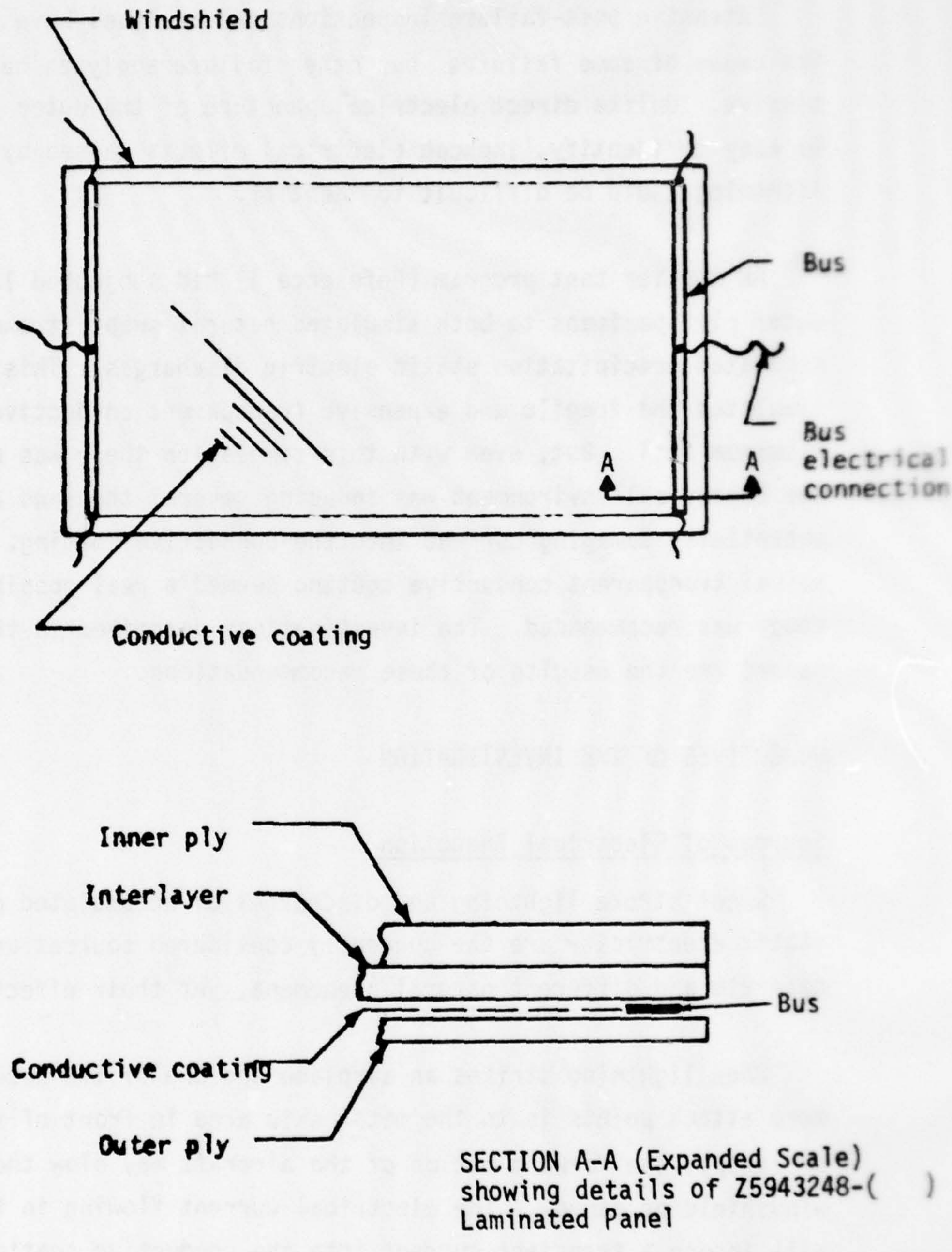


Figure 1. Typical Bus Arrangement Within Windshield.

Extensive post-failure inspections and analyses have clearly identified the cause of some failures, but other failure analyses have not been conclusive. Unlike direct electrical puncture of the outer ply, which may be easy to identify, induced electrical effects caused by P-static or lightning could be difficult to identify.

An earlier test program (Reference 1) had subjected large windshield outer ply specimens to both simulated natural swept stroke lightning and simulated precipitation static electric discharges. This earlier work simulated the fragile and expensive transparent conductive coatings with aluminum foil. But, even with this simulation there was evidence that the electrical environment was inducing several thousand amperes of potentially damaging current into the conductive coating. Damage to an actual transparent conductive coating seemed a real possibility. Further study was recommended. The investigations described in this present report are the results of those recommendations.

OBJECTIVES OF THE INVESTIGATION

Sources of Electrical Induction

Swept stroke lightning and discharges of accumulated precipitation static electricity are the currently considered sources and are caused by separate and different natural phenomena, yet their effect may be similar.

When lightning strikes an airplane and one of the necessary two or more attach points is to the metal skin area in front of the windshield or canopy, the forward motion of the aircraft may blow the stroke across the windshield or canopy. The electrical current flowing in the ionized flash will induce a transient current into the conductive coating within the glass or plastic. If a lightning re-strike occurs during the wind blown passage of the arc across the windshield or canopy, a very strong magnetic field is created. This re-strike current can reach levels as high as 100,000 amperes, although the current is usually much less than this.

(Reference 2 gives a good electrical description of lightning.) The conductive coating and its external circuits, or grounding connections in the case of an RCS coating, act as the secondary winding of a transformer while the lightning flash acts as the primary winding. The result can be a high level transient current induced in the conductive coating and connecting bus strips.

Swept stroke lightning paths across a canopy or windshield, especially with a simultaneous re-strike, are infrequent, but possible occurrences. However, a far more probable source of induced electrical transients is precipitation static, since in-flight impact with snow and ice crystals is a very frequent occurrence.

When airborne particles, especially ice crystals, impact on an insulating surface such as a windshield, the rubbing action creates triboelectric charging of the particles and the windshield. The particles assume one electrical charge and the windshield takes on the opposite charge. A similar charging action is taking place on all other surfaces of the airplane which are rubbed by the airborne particles. However, unlike the metal parts which conduct electricity, the plastic or glass surface of the windshield or canopy does not provide a conductive path and the incremental charge caused by each particle is bound to the insulating surface.

With time, the total bound charge will increase in intensity until something breaks down. It may be the surface insulating material of the windshield or canopy, in which case the material will puncture and the external electrical charge will flow to the conductive transparent coating and on to the aircraft structure through some connecting path. Dielectric puncture, if it occurs, will most probably ruin the long-term usefulness of the canopy or windshield.

If the dielectric is not punctured, the air on the outer surface will undergo dielectric breakdown, sometimes producing a rather spectacular looking electrical discharge flash. The flash causes a rapid discharge

of the previous charge that had slowly accumulated between the outer side of the windshield or canopy and the electrical coating. The result is a high intensity current transient in the conducting film and in the connecting buses and circuitry.

General Test Objectives

This investigation had, as its objectives, the selection of appropriate and representative windshield and canopy specimens incorporating transparent conductive coatings, and the exposure of these specimens to laboratory produced electromagnetic fields of the type that might be encountered due to swept stroke lightning or precipitation static discharges. The specimens were to be heated by passing electric current through the conductive coating, since heating is a frequent reason for having the coating and the heating current is often a precipitator of the final demise of the coating after initial damage by some other cause.

SECTION II

TEST PLAN AND APPROACH

SPECIMEN SELECTION

Criteria for Selection

Cost was a very important restraint on the whole program. The total cost was, in many ways, closely related to the number of specimens and the size of the specimens. Some of the more important criteria were as follows:

- o Size - the specimens should be sufficiently large to be representative of the surface area of real aircraft windshields or the frontal area of canopies. Also, static charges on small specimens would not reach a potential sufficient to pose a realistic puncture or surface flashover potential.
- o Material - the materials and the methods of manufacturing the finished specimens should be representative of an actual aircraft part. The previous test program (Reference 1) had verified that an acrylic outer ply would hold a larger static electric charge than the various aircraft quality glass candidates. Other studies had indicated that the outer ply should be at least 0.085-inch thick (References 1 and 3). The interlayer and inner ply definition were also dictated by the studies of Reference 3.
- o Electrically Conductive Coating - The resistivity of this coating should be representative of an actual anti-icing or RCS coating. A coating resistivity of between 15 and 20 ohms per square was specified. The bus bar configuration should also be representative of an actual aircraft part. A deletion line - an insulating line separating a heated and an unheated portion of a conductive coating - should be included to permit the

investigation of possible internal arc-over between the two coated segments during the period of the induced electrical transient.

- o Quantity - Funding restraints would not allow sufficient quantities of specimens of adequate physical size to permit a statistically accurate program, yet it was felt that very good information could be obtained with a minimum number of specimens. It was further considered important to separate the effects of the lightning environment from the static electric environment, and to study the effects of deletion lines.

FINAL SPECIMEN SELECTION

Cost and manufacturing restraints coupled with the above criteria resulted in the final selection of four specimens; two for lightning tests and two for static electric tests. The specimens for one test were to be the same type as those for the other test, but one of the two types was to have a deletion line dividing the conductive coating into two halves, with separate bus bars for each half. The two basic types of specimens are detailed in Figure 2. Sierracin/Sylmar was the manufacturer of the specimens. The conductive coating was their production type gold-based coating, Sierracote 303.

SPECIMEN MOUNTING

Electrical Requirements

The static electric tests of Reference 1, showed that the electro-mechanical geometry of the area surrounding the transparency has a strong influence on the surface discharge characteristics. Furthermore, a realistic test would require that the edge of the laminated transparency be dielectrically insulated. Otherwise, a surface discharge might seek a path to ground by arcing around the edge and entering the electrical bus or conductive coating. This type of entry path might damage the coating, and is not typical of a well constructed windshield or canopy.

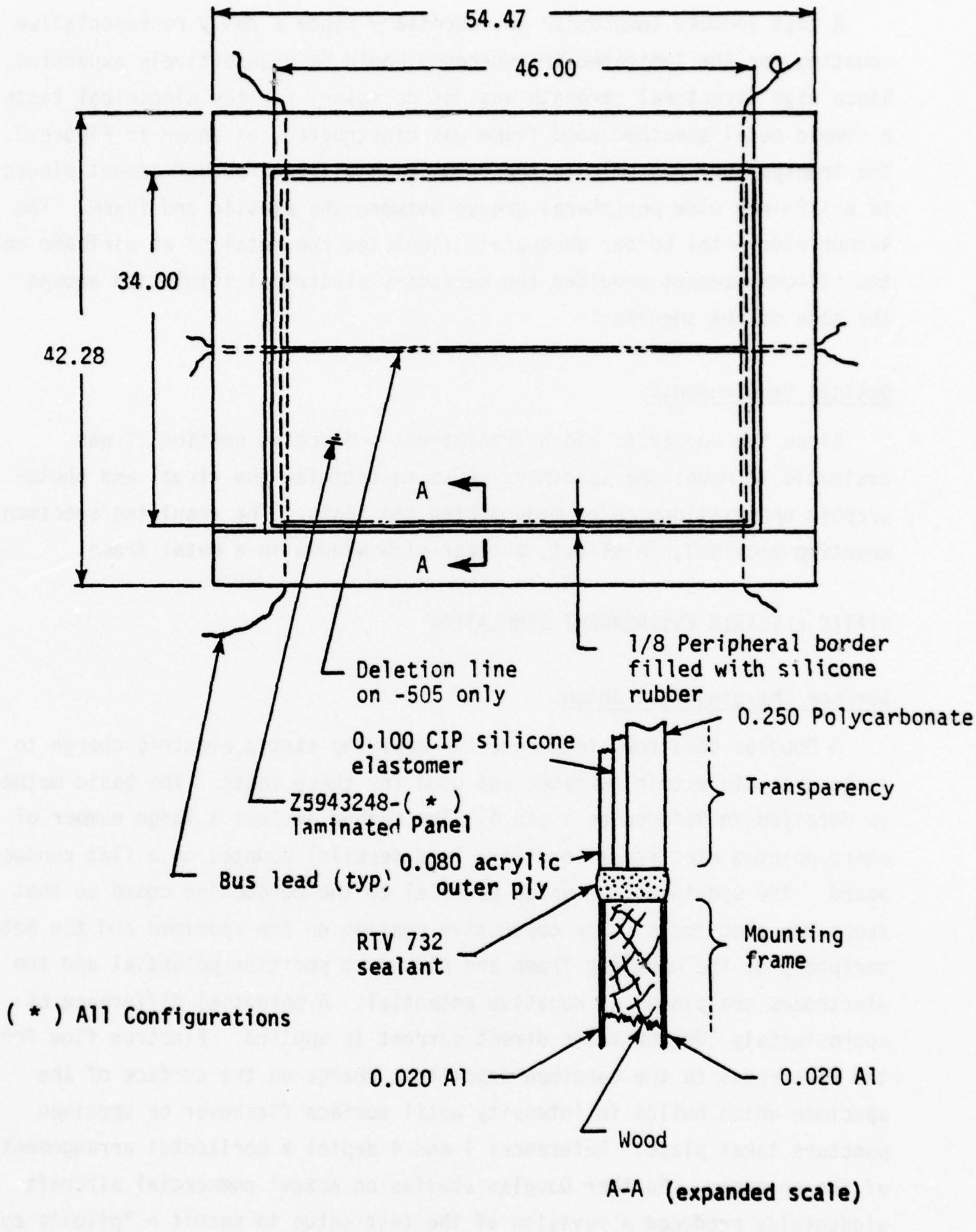


Figure 2. Z5943248-(*) Laminated Panel Test Specimens.

A cost induced compromise was necessary since a fully representative mounting for the laminated transparency would be prohibitively expensive. Since high structural strength was not necessary for the electrical tests, a simple metal sheathed wood frame was constructed, as shown in Figure 2. The transparency was held in the frame with silicone rubber cement placed in a 1/8-inch wide peripheral groove between the plastic and frame. The 4-inch wide metal border adequately simulated the metal of an airframe and the silicone cement provided the necessary electrical insulation around the edge of the specimen.

Optical Requirements

Since the specimens had a transparent conductive coating it was desirable to mount the specimens so as to optimize the visual and photographic observations to be made during the tests. The resulting specimen mounting provided, in effect, a clear-view window in a metal frame.

STATIC ELECTRIC ENVIRONMENT SIMULATION

Surface Charging Test Setup

A Douglas developed technique for applying static electric charge to large area dielectric surfaces was used for these tests. The basic method is detailed in References 1 and 4. The method employs a large number of sharp pointed electrodes (ordinary lead pencils) mounted on a flat conducting board. The specimen is mounted parallel to the conducting board so that it faces the electrodes. The conductive coating on the specimen and the metal periphery of the mounting frame are placed at positive potential and the electrodes are placed at negative potential. A potential difference of approximately 100,000 volts direct current is applied. Electron flow from the electrodes to the specimen deposits a charge on the surface of the specimen which builds in intensity until surface flashover or specimen puncture takes place. References 1 and 4 depict a horizontal arrangement of the specimen. Further Douglas studies on actual commercial aircraft windshields produced a revision of the test setup to permit a "pilot's eye" view of the discharge phenomena. This technique was carried through for the work covered by this report.

A mounted specimen was bolted to a large plywood board which had a hole cut in the middle, equal in size to the specimen. The plywood board was mounted vertically so that a camera could photograph the full surface of the specimen. Figure 3 shows an overall view of the precipitation static test simulator. A specimen is shown mounted on the black plywood board. The high voltage control console is shown on the right. The equipment was installed in a room that could be totally darkened to permit surface flash photography. Figure 4 is a view looking in at the left side of Figure 3. Figure 4 shows the pencil electrodes on the left and the specimen board on the right.

Induced Current Measurements

When a surface discharge takes place a large electrical transient is induced into the conductive coating of the specimen. It was thought desirable to measure this transient. However, the high frequency nature of the transient and the rather high ambient electromagnetic interference level caused by the high voltage charging circuitry presents measurement problems which would have taxed the funding of this program. Since full knowledge of the discharge current characteristics was not necessary for the main objectives of this program, a simplified measurement scheme was employed.

In an actual, well designed aircraft installation each electrical bus connected to the conductive coating would be at or near fuselage ground potential. Therefore, the specimen buses were paralleled and returned to ground via a wire that passed through the aperture of a current probe (Stoddart 91550-1). The probe sampled the current in the wire without actually making an electrical contact to the wire. The output of the probe was terminated in the required 50-ohm impedance and then attenuated in a 10:1 probe and fed to a Tektronix 466 memory oscilloscope. The stored trace could be photographed, as desired. This technique afforded better stray signal shielding than the electrical shunt method previously used in Reference 1.

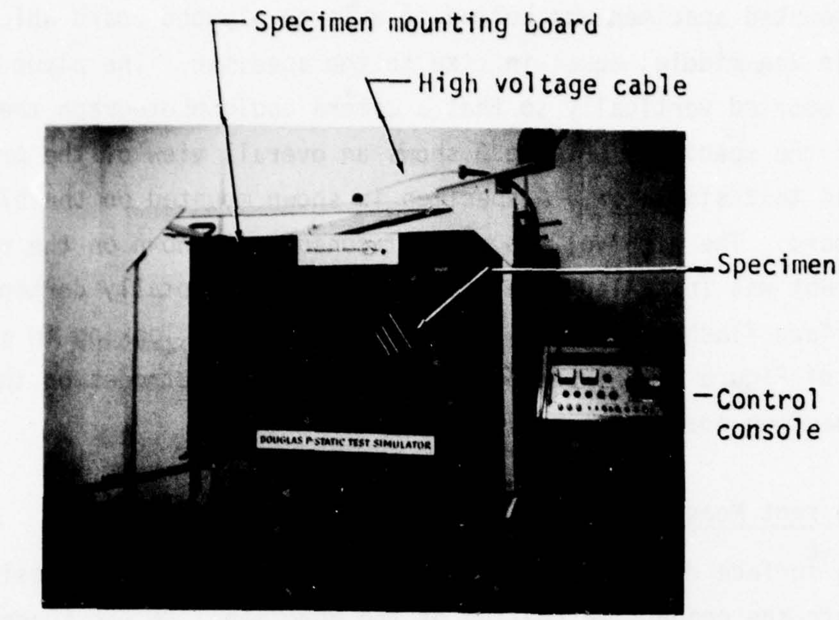


Figure 3. P-Static Test Simulator - Overall View.

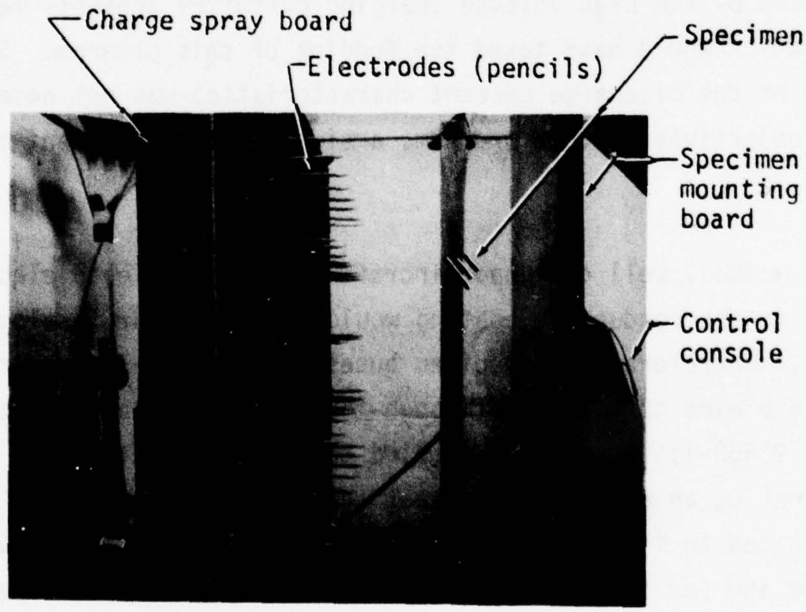


Figure 4. P-Static Test Simulator - Side View.

Photographing Surface Discharges

A tripod-mounted Polaroid camera was placed in front of the specimen. A dual exposure technique was employed. One shot was taken with the lights on to record the location of the specimen and enough of the surroundings to provide a frame of reference. Next, the lights were turned off, the high voltage turned on and the camera shutter opened to provide a time exposure. Everything remained dark except for some corona at the electrode tips and other corona spots around edge anomalies on the specimen mounting periphery. When the static electric charge could no longer be sustained by the air on the specimen surface, a discharge took place. The brilliant flash was then recorded through the open shutter on the camera.

The camera was placed directly in front of the specimen to reduce distortion of the picture as much as practicable, as it was desired to be able to correlate the flash locations with any observed damage to the electrical coating in the specimen. Surface discharges are a random happening; their frequency and location cannot be predicted ahead of time. Therefore, not all discharges were photographed, but a count of the number of discharges was kept.

SWEPT STROKE LIGHTNING ENVIRONMENT

Laboratory Simulation of Lightning

Natural swept stroke lightning is very difficult to simulate in the laboratory. No totally satisfactory method is known to have been developed. One of the principal contributors to this problem is that the natural phenomena is not too well defined. Another problem is that in nature, both very high voltages (many megavolts) and high currents are involved along with the forward motion of the aircraft. Man-made facilities have not fully simulated all of these ingredients.

As discussed in the introduction, the ionized swept channel produces a strong magnetic field which will induce a current into the conductive coating of the windshield or canopy. For the purpose of these tests only the magnetic field was simulated. This was accomplished by passing the simulated re-strike current through a 5/8-inch diameter aluminum pipe that was placed against the outer surface (the acrylic ply) of the specimen. The resulting magnetic flux that surrounded the pipe during the discharge was available for induction into the conductive coating within the specimen.

Figures 5 and 6 show a specimen with the "lightning path" pipe across the surface. Figure 5 shows the pipe positioned over the deletion line down the center of the Z5943248-505B specimen. A similar location for the pipe was used with the Z5943248-1B specimen (without the deletion line). Figure 6 shows the pipe centered over the lower half of the conductive coating of the -505B specimen.

Figure 7 is a schematic diagram of the lightning generator.

Lightning Current Instrumentation

Drive current from the lightning generator was indicated by means of a resistive shunt in series with the capacitor discharge current. The output of the shunt was connected by a terminated, double shielded coaxial cable to a remotely located Tektronix 466 memory oscilloscope. Current in the conductive coating of the specimen was measured by interconnecting the bus bars with a shorting wire. The Stoddart 91550-1 current probe was placed around the shorting wire. One of the instrumented buses was also directly connected to the ground plane which also served as the reference conductor for the lightning generator.

For the -505B specimen (with the deletion line), one-half of the split conductive coating was directly tied to ground by connecting each bus to the metal periphery of the specimen mounting frame. This metal periphery was also connected to the test setup ground plane by a low impedance metal angle plate. This uninstrumented portion of the conductive coating was

Figure 5. Specimen with Lightning Path Pipe Over Deletion Line.

Figure 6. Specimen with Off-Center Lightning Excitation.

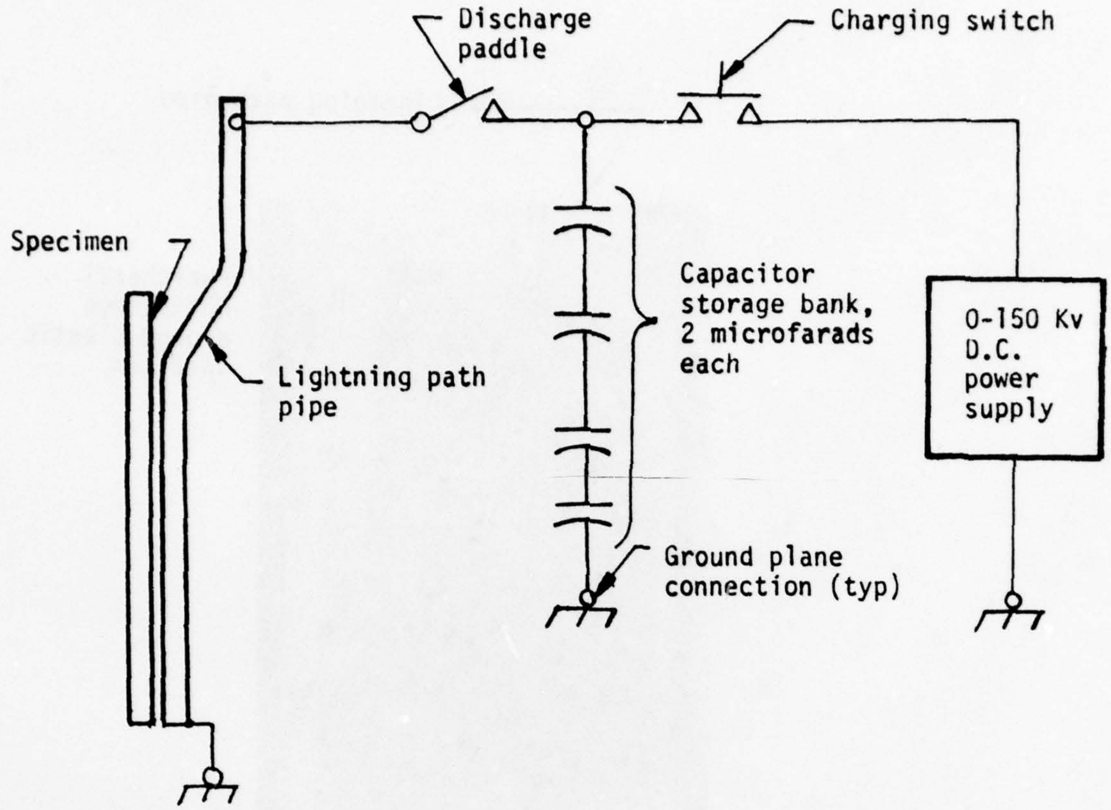


Figure 7. Schematic Diagram of Lightning Simulator.

grounded in this way to simulate that portion of a typical windshield which has an unheated conductive coating, which is used to complete the optical and RCS coverage of the total transparent area.

DAMAGE ASSESSMENT

Overall Objective

The damage assessment methods were tailored to the goal of determining if and to what extent P-static and swept stroke lightning would damage the conductive, transparent, heated or RCS coatings used in aircraft windshields and canopies.

Visual Inspection

The least complicated and one of the best damage assessment methods is careful inspection by the human eye. The gold-based conductive coating used in these specimens could easily be seen in transmitted and reflected light. Flaws within the laminates were also visible.

Visual inspection using polarized light was also employed. A polarized light source was held on one side of the specimen and a polarizing sheet was held on the opposite side of the specimen. The polarizing sheet was rotated for maximum light attenuation. The combination of source and viewing sheet were then moved together over the surface of the specimen to observe transmission anomalies. These observations were made for both the heated and cold conditions of the specimen.

Heating the Specimens

One of the key methods of damage assessment required that the specimens be heated by passing current through the conductive coating. The specimen geometry and electrical bus connections were chosen to permit this heating. This was considered a legitimate approach, even if one were only interested in using a coating for RCS purposes and not for heating because the resistivity of a heated coating would be in the same resistivity range as a coating designed specifically for RCS control.

The specimens were hung vertically against a thermally stable wall and electric power was supplied to the buses. A variable-voltage transformer supplied monitored 60-cycle voltage. A 1- by 4-foot temperature reference specimen of 1/8-inch thick acrylic sheet was hung vertically adjacent to the specimen under test. A small area on the upper end of this sheet was heated from behind by an electrically heated aluminum plate. A small chromel-alumel foil-type thermocouple (RdF Corporation No. 20112 125) was placed on the outer surface opposite the heater. Constant voltage was applied to the heater to establish a known hot surface reference temperature. A similar second thermocouple was placed on the lower portion surface of this acrylic sheet to permit measurement of the ambient surface temperature.

An acrylic reference temperature sheet was chosen so that its surface emissivity would be the same as that of the acrylic covered specimens.

Figure 8 is a photograph of the simple but very effective setup for heating the specimen. The acrylic reference sheet is on the right of the specimen. The voltmeter-ohmmeter is on the junction box to the left of the specimen. The variable voltage transformer (Variac) is sitting on the stool and the smaller Variac used to power the reference high temperature spot is on the floor. The black curtain at the extreme right is used to eliminate reflections in the smooth surfaces of the specimen and reference sheet when the IR camera (discussed later) is viewing the surfaces.

Bus-To-Bus Electrical Resistance

Changes in the resistance of the conductive coating are a good indicator of damage to the conductive coating or coating-bus interface. Bus-to-bus resistance measurements were made before and after each environmental exposure sequence.

Surface Temperature Relationship to Coating Damage

Changes in the surface temperature pattern are also a good indicator of changes in the resistive coating when the coating is used as a source of heat. A coating which has been primarily designed for heating will usually present a uniform resistivity or a smoothly graded resistivity. Large or abrupt changes in the uniformity of a resistive coating would produce hot or cold spots which could be detrimental to the physical integrity of the windshield and to its usefulness in an icing environment.

A progressive pattern of changing surface temperature distribution, resulting from exposure to the static electric discharging or lightning, would indicate changes in the resistive distribution within the coating. Small, localized resistance changes caused by the induced current from the P-static or lightning environment might trigger additional deterioration when the heating current flows through the coating. This would be the case

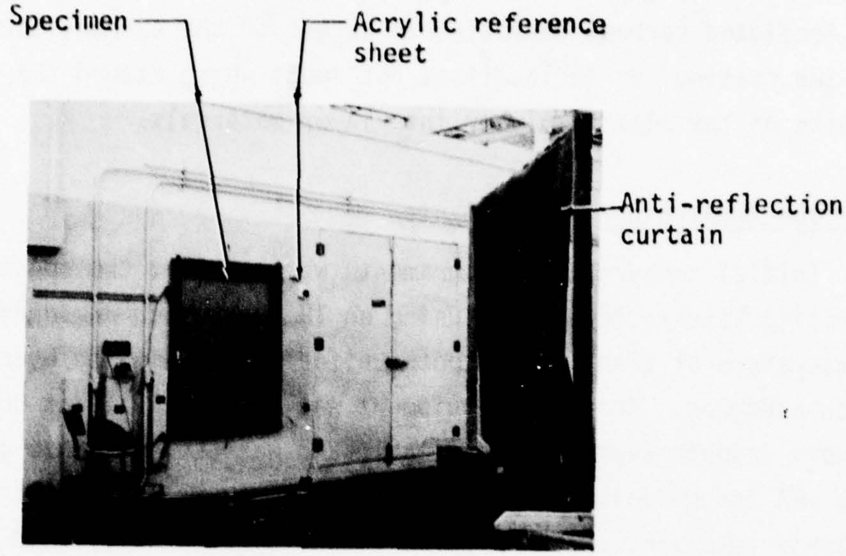


Figure 8. Specimen Heating Test Setup.

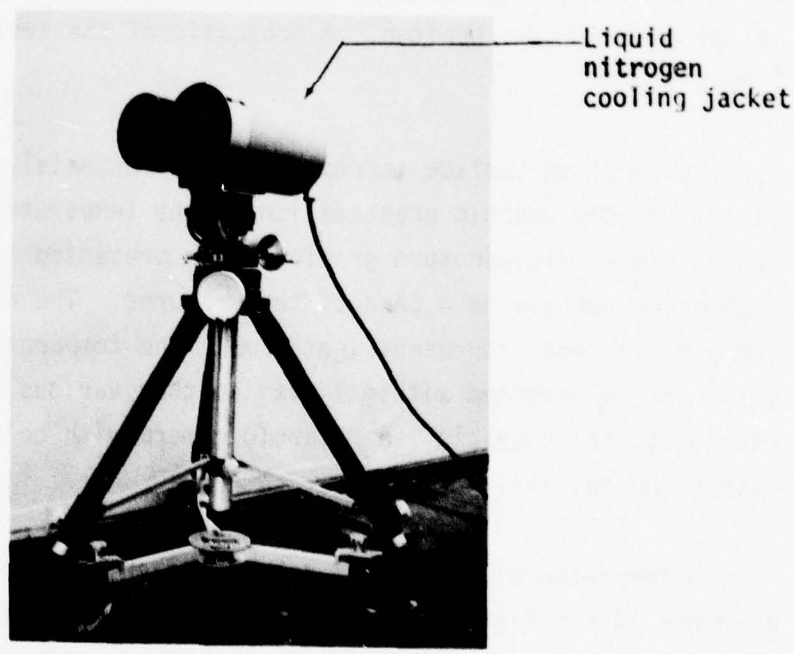


Figure 9. Thermovision IR Camera.

when new distributions of the current, caused by coating damage, result in localized current densities in excess of the current carrying capabilities of the coating, or in localized hot spots which exceed the temperature limits of the plastic ply or interlayer materials.

Surface Temperature Measurements

Initial temperature measurements were made at the specimen supplier's facility (Sierracin/Sylmar) using an IR gun, which measured the surface temperature at twenty (20) spots uniformly distributed over the surface of each specimen. This same equipment was not available at Douglas. However, a more graphic system was available and was used for this project. It is the AGA Thermovision 680 system. This is a Swedish product that may be quickly described as an infrared closed circuit television system. A special IR camera, Figure 9, scans the specimen surface. A black and white read out of the thermal gradient on the specimen surface is presented on the Model 102 Thermovision mainframe, and color isotherms are presented on the CM 700 Color Monitor. A schematic of the test setup is shown in Figure 10.

The specimen surface is scanned in approximately 0.06 second, which permits a very graphic presentation of any temperature changes that may be taking place. Temperature gradients are presented in ten different colors. Each color represents a band of temperatures. The colors, as presented on the picture tube, represent isotherms. The temperature range within each color can be selected within limits so that various degrees of temperature resolution are possible. A Polaroid camera with color film was used to record the results.

Thermovision pictures were taken of each heated specimen before exposure to the P-static or lightning environment and after each step in the exposure cycle. Measurements were not made during the exposure as it was not believed necessary, and doing so would greatly increase the complexity and cost of the tests.

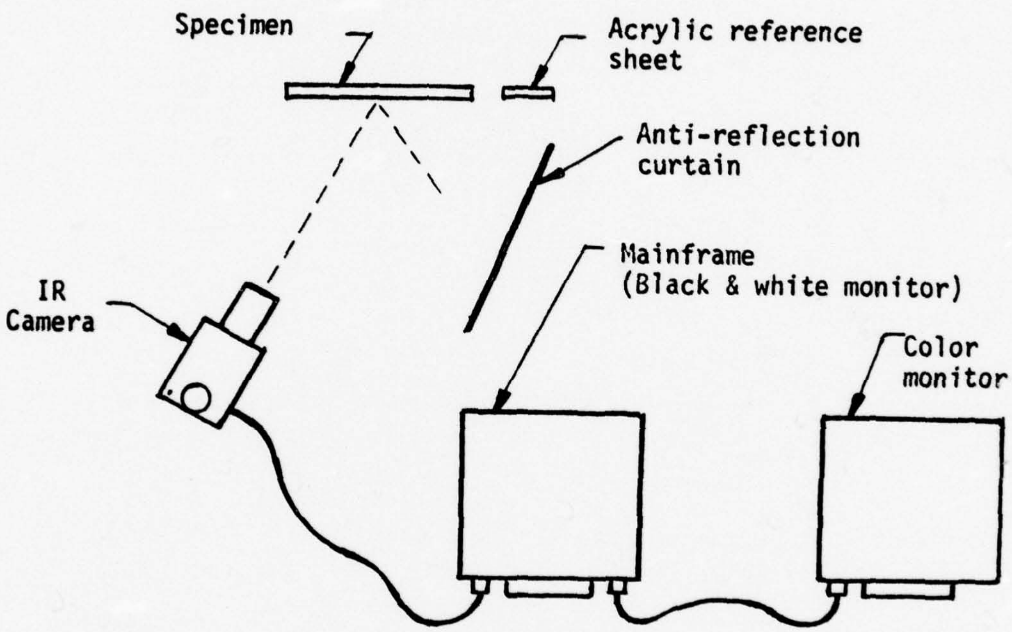


Figure 10. Plan View of Thermovision Test Setup.

SECTION III

CONDUCT OF THE TESTS AND TEST RESULTS

INITIAL TEMPERATURE AND RESISTANCE MEASUREMENTS

Manufacturer's Data

The manufacturer's temperature data are shown in Figures 11a, 11b, 11c and 11d. These data were taken on the unmounted specimens with the plane of the material vertical. The bus-to-bus voltage was 50 volts.

Initial Resistance Measurements

Resistance measurements were made from bus-to-bus using a Danameter Model 2000 volt-ohmmeter. The initial readings were made before any heating voltage had been applied by Douglas; however, Sierracin/Sylmar had applied heating voltage prior to delivery of the specimens. The initial data are included in Table I along with the other readings taken as the test proceeded. The specimens are referred to by the dash number of their basic Z5943248 drawing number. Upper and lower designations for the -505A and -505B specimens refer to the two sections of the divided coating, as referenced to the word "UP" marked on the mounting frame. The -1A and -1B specimens had no division; there was only one coating with a bus bar on each of two opposite sides.

Initial Thermovision Measurements

Baseline Thermovision measurements were made on each specimen as that specimen was started through its environmental exposure cycles. Therefore, it could be hours or days between different baseline measurements. The Thermovision clearly displayed regions of slightly varying temperature on each specimen. Direct comparison of the Thermovision color pictures was not easy because the color-temperature calibration will vary due to the ambient temperature, and especially because of slight setting adjustment changes on the mainframe and color monitor. This is not to imply poor accuracy with the Thermovision, as a calibrated color picture of a

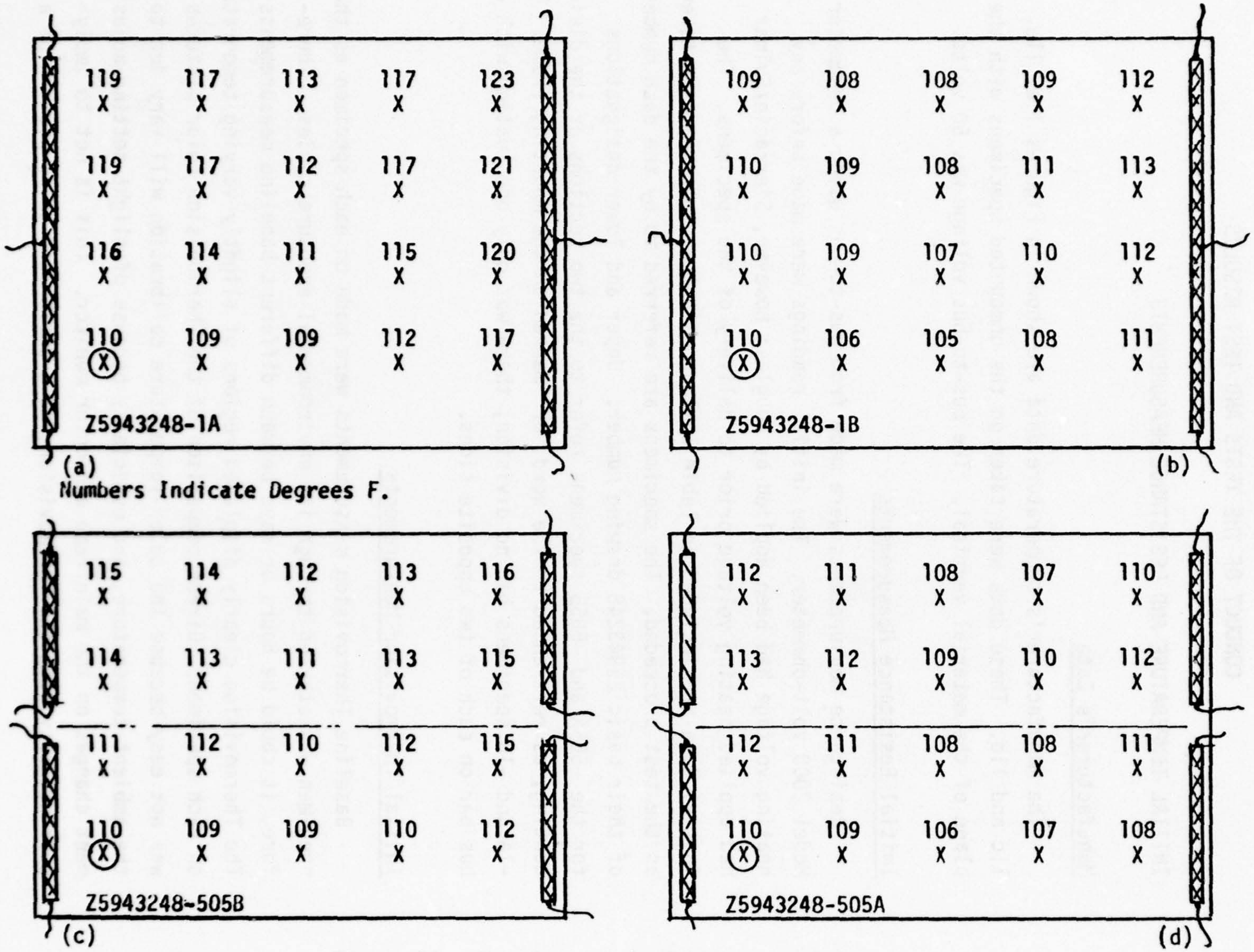


Figure 11. Manufacturer's Temperature Data.

TABLE 1. RESISTANCE MEASUREMENTS

(A) P-static Test Specimens

Specimen	-1A	-505A
Initial reading	20.3 Ω cold	Upper 39.5 Ω cold Lower 40.3 Ω cold Paralleled 19.9 Ω (Calculated)
After first static discharge series	20.6 Ω cold 21.1 Ω hot	19.8 Ω cold 20.0 Ω hot } Measured Parallel
After second static discharge series	21.1 Ω cold	20.0 Ω hot (measured parallel)

(B) Lightning Test Specimens

Specimen	-1B	-505B
Initial reading	21.6 Ω cold 21.7 Ω hot	Upper 38.4 Ω cold Lower 37.9 Ω cold
After first lightning exposure - see text	61.7 Ω cold	Upper 38.3 Ω cold Lower 38.6 Ω cold Paralleled Ω19.3 Ω hot
After 2nd lightning exposure (75 KV)		Upper 38.5 Ω cold Lower 38.1 Ω cold Paralleled Ω 19.4 Ω hot
After 3rd lightning exposure (1st 150 KV)		Upper 41.4 Ω cold Lower 39.0 Ω cold Paralleled 20.3 Ω cold Paralleled 20.5 Ω hot
After 4th lightning exposure (2nd 150 KV)		Upper 42.5 Ω cold Lower 54.4 Ω cold Paralleled 23.1 Ω cold

specific temperature pattern can be read very easily. The great advantage of the Thermovision equipment is its ability to present a dynamic picture of the whole surface under observation in essentially real time. The temperature distribution could be observed from a cold start until it reached a stable condition. Because of the thermal lag in the material, temperature stability took over a half-hour with an applied bus-to-bus voltage of approximately 45 volts. Final temperature plots were photographed after about one hour.

The baseline thermal plots for all the specimens indicated a warmer region near the center of the upper edge, and a cooler region near the lower edge of the vertically supported panels. Figure 8 shows that the upper edge during the Thermovision tests is in reality, the right hand edge with reference to the "UP" marking on the specimen. This orientation of the specimen was chosen to best fit the aspect ratio of the IR camera scanning system since the liquid nitrogen in the camera cooling system somewhat restricted physical orientation of the IR camera as might be done with an ordinary photographic camera.

The warmer upper edge of the specimens was at first believed to be the normal result of rising convection currents. Indeed, this was the actual case, to some extent. One specimen (-505A) was also hung on its side (the "UP" marking now on the bottom) and allowed to temperature stabilize for about one hour. During this time the temperature pattern shifted a little to reflect the expected affect of the vertically rising convection currents. However, the change was not as much as expected and the hot edge indication followed the rotation of the panel. (The hot edge was now on the left.) Therefore, it was concluded that convection currents had only a degree F, or so, effect on the measured temperature.

The baseline temperature distribution was generally similar for all four specimens, but each had its identifying differences. The -1A specimen displayed two tight little areas of warmer temperature about one-quarter

of the way up from the bottom near the vertical center (as oriented during the test). These spots were to become more important during the environment exposure runs.

The deletion line (vertical in this test orientation) was evident in the baseline data for the -505B specimen. Slight temperature differences were easily detectable on either side of the deletion line. The black and white presentations in the picture on the mainframe, with its shades of grey instead of color, exaggerated the overall effect of the deletion line and made its presence very easily detected.

Although there were easily detectable differences in the baseline temperature distribution of the four specimens, these differences amounted to only a few degrees F and undoubtedly would not have been cause for rejection had these been actual production aircraft parts. Examples of temperature plots will be presented later as the results of the environment exposure unfold. Reproduction restrictions limit the usefulness of direct black and white copies of the color Thermovision pictures.

STATIC ELECTRIC DISCHARGE EXPOSURE TESTS

First Exposure of -505A Specimen

The -505A specimen, containing a deletion line, was the first specimen mounted in the test simulator. All buses were electrically paralleled and returned to the ground. During the pre-test planning it was predicted that if damage to the gold resistive coating were to occur, it would take place under the surface discharge flash path, and in particular under the "trunk" of the "Oak Tree" flash pattern, as this would be the region of greatest induced current density. For this reason it was hoped that a photograph of the flash could be correlated with any observed burning or damage to the conductive coating.

The unpredictable and highly random nature of the surface flashovers defeated this intent and made it very difficult, if not impossible, to turn the machine on, get a single flash, photograph the single flash, and then turn the machine off before another flash occurred. Two or three flashes took place before the camera shutter was opened. A few more flashes occurred before the high voltage machine was turned off. Fortunately, a close visual inspection of the coating did not reveal any signs of damage at any place. Therefore, it was decided to just keep track of the number of discharges, take photographs of some of the discharges, and conduct a detailed damage assessment after groups of flashes had occurred.

Figure 12 is a photograph of a typical static electric discharge on the acrylic surface of the -505A specimen. The relative current density of the discharge branches can be judged by the photographed intensity of the various branches. Fifty-nine discharges were allowed before the specimen was dismounted from the test simulator for detailed damage assessment. Some of these flashes were weaker and less extensive in area than the single discharge of Figure 12, while some were more intense and with more sub-branches.

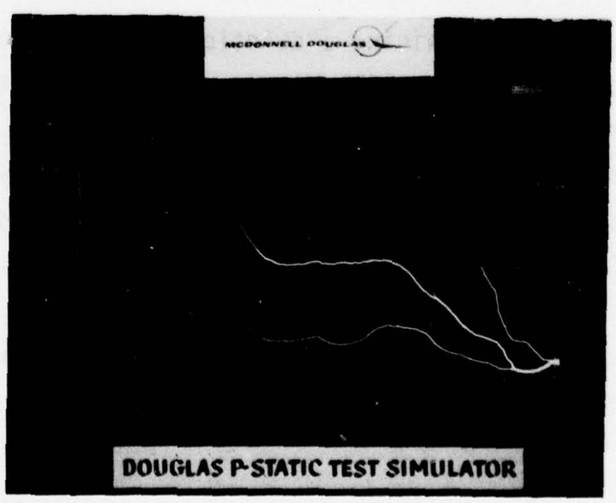


Figure 12. Typical Discharge Pattern on -505A Specimen.

Damage Assessment of -505A After First Exposure Run

The specimen was dismounted from the static test simulator and taken to an area of better lighting where no visible signs of change or damage were noted. Bus-to-bus resistance measurements were made (Table I) and indicated no significant change.

The -505A specimen was next hung in place for Thermovision scanning. No significant thermal pattern changes were noted. A resistance measurement was made while the specimen was warm. The resistance had increased only about 0.2 ohm. This is considered insignificant. The specimen was then returned to the P-static test simulator.

Second Exposure of the -505A Specimen

The second exposure run subjected the specimen to 104 additional surface flashes, bringing the total for runs 1 and 2 to 167 flashes. This may be more than any ordinary windshield or canopy would experience during a normal lifetime of use.

Figure 13 is a photograph made during the second exposure run. This photo is significant because it shows six separate discharge patterns that took place individually at different times during the period the camera shutter was open. Varying intensity flashes from different parts of the surface are clearly visible. The pencil electrodes are visible in the reflected light from the discharge flashes. The corona glow at each pencil tip produces a background dot matrix. At no time during all of this testing was there any evidence of dielectric puncture of the acrylic outer ply. No internal sparking was noticed along the deletion line.

Damage Assessment of -505A After Second Exposure Run

The same procedure, as previously described, was used to conduct the assessment after the second static electric discharge exposure run. Visual, resistance, and Thermovision inspections disclosed no significant changes. Isotherm traces from the Thermovision color photographs for the baseline,

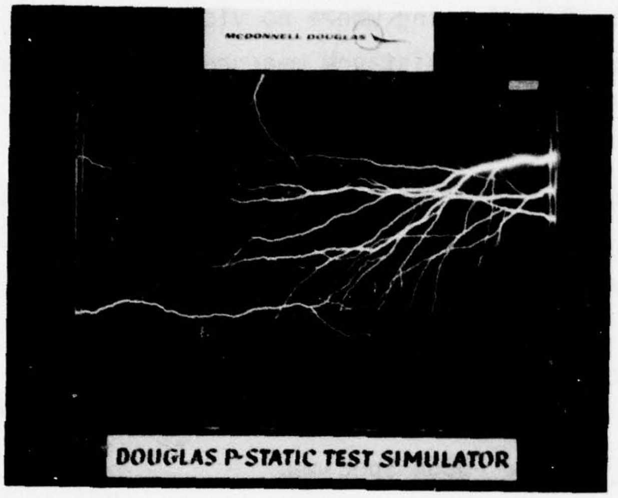
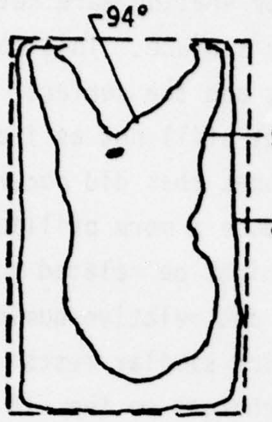


Figure 13. Multiple Exposure Discharges on -505A Specimen.

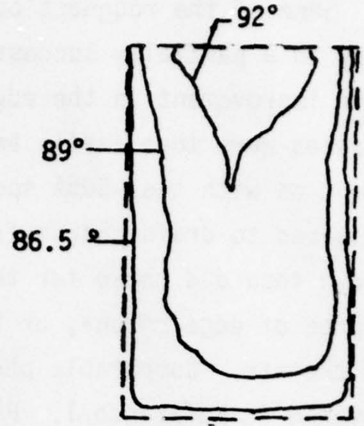
first exposure, and second exposure thermographs are shown in Figure 14. Note that the isotherm lines on the traces do not represent the same temperature for each Thermovision run. The important, easily derived information from the traces is that no significant change in the heating pattern took place. This observation translates to the conclusion that a large number of surface flashes apparently did not induce damaging current into the gold conductive coating of the -505A specimen.

First Exposure of the -1A Specimen

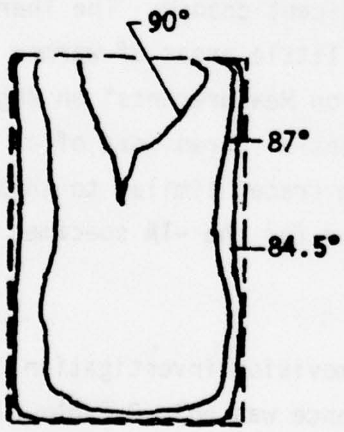
The exposure was conducted the same as for the -505A specimen. The -1A specimen did not reach a discharge condition until approximately 20 percent higher voltage was applied to the test simulator than was the case for the -505A specimen. After flashover was attained, the frequency of flashes was not as fast as with the -505A specimen. A considerable amount of corona appeared around the border of the specimen where the silicone rubber adhesive held the specimen to the mounting frame. The adhesive had not been applied as uniformly as on the -505B. Numerous surface bumps were present. The visual corona appeared to concentrate at these dielectric anomalies.



-505A
Baseline Run
Prior to Exposure



-505A
After First Static
Electric Exposure



-505A
After Second
Static Electric
Exposure

Figure 14. Isothermal Traces on -505A Specimen After Static Electric Discharges.

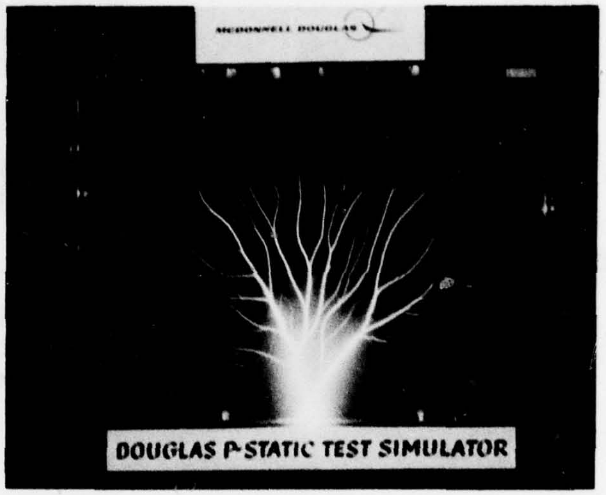
Some of the roughest bumps in the silicone rubber sealing were cut away in a partially successful attempt to smooth the surface. This made some improvement in the edge electrostatic geometry, and the surface flashes were more easily and frequently attained, but still not as frequent as with the -505A specimen. However, the flashes that did occur appeared to drain charge from a larger area and produce a more brilliant flash than did those for the -505A specimen. This might be related to the degree of edge corona, or to the surface conditions and relative humidity of the air. Comparable phenomena were observed during similar tests covered in Reference 1. Photographs of typical discharges on the -1A specimen are shown in Figures 15A and 15B. This first exposure run was conducted on a Friday. When the second exposure run (below) was resumed, it was Monday. The surface flashes for the second run had more nearly the characteristics of those seen on the -505A specimen.

Forty-one flashes were allowed on this first exposure run.

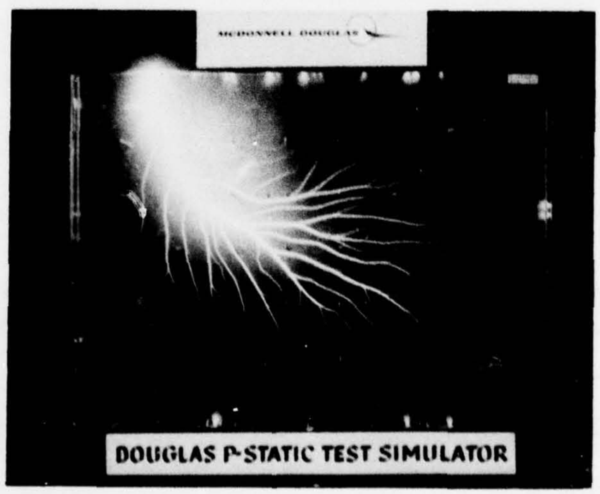
Damage Assessment of -1A After the First Exposure Run

The visual inspection yielded no indication of damage. Resistance measurements (Table I) also indicated no significant change. The Thermovision inspection did show a change in the two little areas of warmer temperature discussed under "Initial Thermovision Measurements" on Page 23. They appeared to be more accentuated and the central cores were of a slightly higher relative temperature. Isotherm traces similar to those previously discussed for Figure 14 are presented for the -1A specimen in Figure 16.

The resistance was measured after the Thermovision investigation and while the specimen was still warm. The resistance was only 0.5-ohm higher, which is approximately the same difference noted under similar circumstances for the -505A specimen. The -1A specimen was then returned to the P-static test simulator.

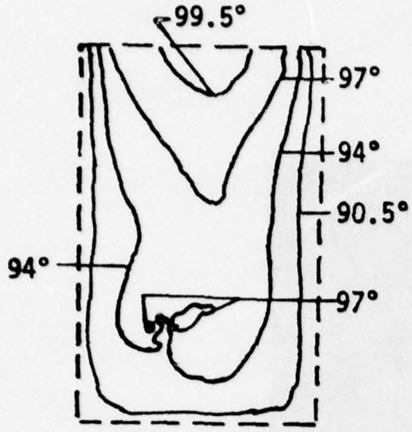


(A)

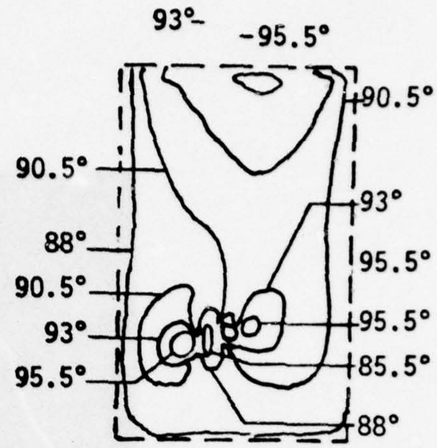


(B)

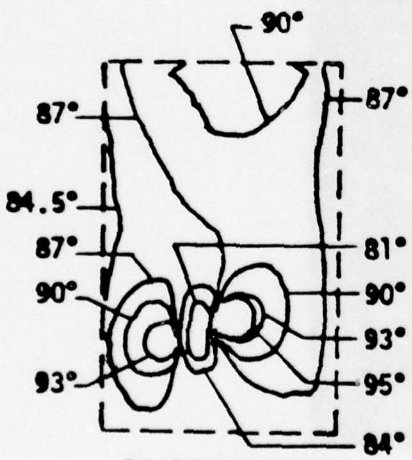
Figure 15. Surface Discharges During First Exposure Run on -1A Specimen.



-1A Baseline Run
Prior to Exposure



-1A After First
Static Electric
Exposure



-1A After Second
Static Electric
Exposure

Figure 16. Isothermal Traces on -1A Specimen After Static Electric Discharge.

Second Exposure of the -1A Specimen

A weekend had intervened between the first and second exposure runs. As previously noted, the characteristics and frequency of the flashes during this second run were less severe than on the previous Friday. No conclusive explanation is available because the relative humidity in the room could not be measured at that time.

Sixty-five additional surface flashes were allowed during the second run for a grand total of 124 flashes. This compares with a total of 163 flashes on the -505A specimen. A photograph of one of the second run surface flashes is shown in Figure 17.

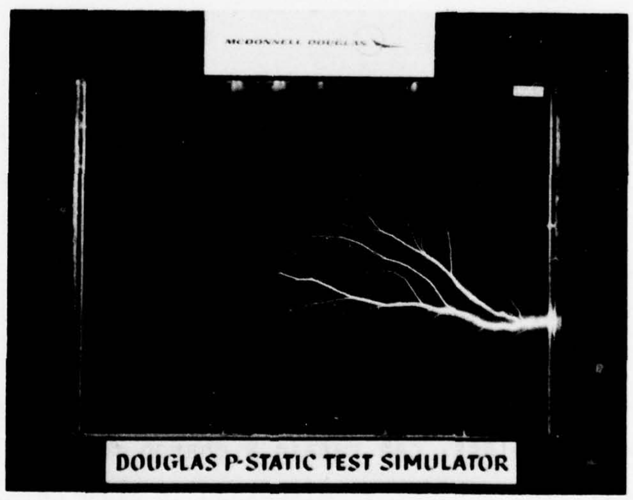


Figure 17. Surface Discharges During Second Exposure Run on -1A Specimen.

Transient Current Measurements of the -1A Discharge Current

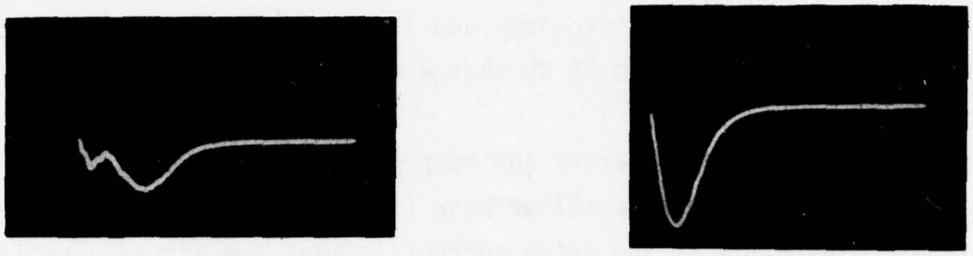
The discharge current in the ground circuit of the conductive coating was measured, as described in Section II, Page 7. Some difficulty was experienced in obtaining good oscilloscope traces. This was partly due to the elusive timing of the discharge, and partly due to insufficient shielding in the test setup to eliminate false oscilloscope triggering caused by the ambient electromagnetic interference. It was not practicable to correlate a photograph of the discharge flash with the oscilloscope trace of the current in the conductive coating. Figure 18A is a trace of a flash which apparently was several microseconds in forming, as evidenced by the double hump. It is also possible that this represents two nearly coincident smaller discharges. Figure 18B is a very clean picture of one larger flash. The reduced scan mode of the Tektronix 466 storage oscilloscope was used for these measurements. The smaller graticule divisions are to be used in interpreting these traces. The peak amplitude of Figure 18B represents about 100 amperes with a rise time in about 1 microsecond.

Surface Charge Retention

During these present tests the -1A specimen, on one occasion, held a significant charge for over 18 hours after application of the charge spray. This good electrical insulating characteristic of clean, dry plastic surfaces might be detrimental to the working safety of ground crews, and is mentioned here for this purpose. In contrast to the possible long term charge retention possibilities of plastic surfaces, previous observations have shown that some glass surfaces with poorer insulating qualities, especially soda lime glass, can retain a charge for only seconds to a very few minutes. The subject is discussed in more detail in Reference 1, Section V.

Damage Assessment of -1A After the Second Exposure Run

Visual inspection showed no signs of damage. Resistance measurements also indicated no change (Table 1). The Thermovision inspection did show progressive changes in the two areas previously noted. Apparently there was



(a) (b)

1 μ sec/div

≅ 20A/div

Figure 18. Oscilloscope Trace of Current in Conductive Coating in -1A During Surface Discharge.

a continuing slight deterioration in the homogeneity of the resistance coating in this area of the specimen. Figure 16 also shows the isotherm tracings for the specimen after the second static electric discharge series. Although there had been a very noticeable change in the isotherm plot between the baseline run and the last run, it is doubtful that these changes would degrade the ability of the resistive coating to perform a satisfactory anti-icing function if it were a part of an actual aircraft windshield. However, there is the unanswered question of whether the continuous cycling of heating current, as would be encountered in an actual windshield, would cause the discharge induced changes in the resistive coating to further change and develop into an unsatisfactory condition.

SIMULATED SWEPT STROKE LIGHTNING TESTS

First Lightning Exposure Run on the -1B Specimen

Initial resistance and Thermovision plots were run on the -1B specimen. It was then mounted in the frame with the 5/8-inch diameter conductor across the acrylic surface, as discussed in Section II, Page 14. Preliminary

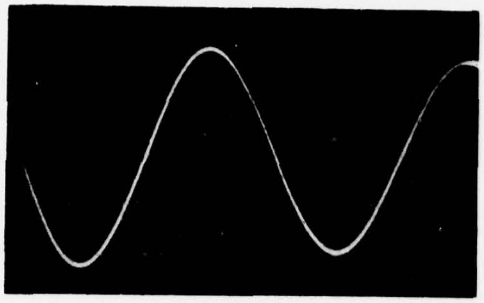
adjustments of the discharge circuitry and instrumentation were made at reduced amplitudes (from 10 to 25 KV charge on the capacitor).

Figure 19 is a series of drive and response waveforms run at 25 KV charge on a 0.54-microfarad capacitor bank (four 2 microfarad capacitors in series). Figure 19a is the drive current as measured across a resistive shunt. The initial peak of this damped wave represents 8 kiloamperes. Figure 19b is a detailed study of the early time characteristics of the waveform of Figure 19a. Figure 19a is at 2 microseconds per division, while Figure 19b is at 0.05-microsecond per division. The vertical response of Figure 19b is 2.5 times as sensitive as for Figure 19a, and indicates a clean front end structure. Figure 19c is a trace of the response signal in the bus-to-bus current flowing in the -1B specimen. It was measured using the Stoddart 91550-1 current probe around the wire which interconnected the buses. Figure 19c is to the same time scale as Figure 19a (2 μ sec./div) and shows that for time beyond the initial induced transient, the waveform has the same frequency as the drive current. Note that with the exception of Figure 19a, all the other Figure 19 traces used the reduced scan feature of the 466 oscilloscope wherein the small graticule squares apply.

Figure 19d is a detailed study of the fast time characteristics of the waveform of Figure 19c. Figure 19d was taken at the same vertical sensitivity as Figure 19c, but at 0.2-microsecond per division. The transfer impedance of the Stoddart current probe is higher for high frequencies than for low frequencies. Therefore, the amplitude of the initial, fast rising (negative going) transient in Figure 19b represents 41 amperes, while the first positive peak of the lower frequency portion of the wave represents 36 amperes.

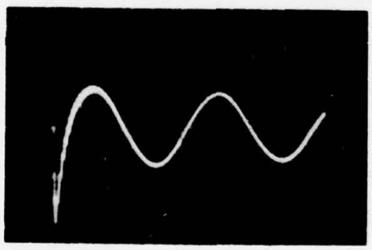
<u>Damage Assessment of -1B After First Lightning Exposure Run</u>

This assessment consisted only of visual inspection, which showed no change. Since the induced transient currents during the preliminary lightning exposure had been low, it was reasoned that further detailed inspections were not necessary.

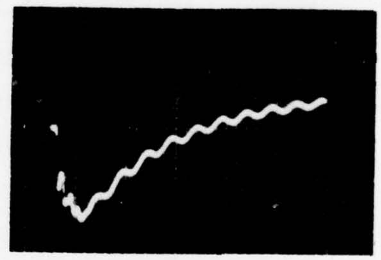


(a) Lightning drive
2 μ sec/div
8K amp first peak
(3.56K A/Div)
(Large graticule squares)

(b) Early time characteristics of (a) 0.05 μ sec/div see text.



(c) Response in conductive coating from excitation of (a) above.
2 μ sec/div
first negative peak ≅ 41A
first positive peak ≅ 36A.



(d) Early time characteristics of (c) 0.2 μ sec/div same vertical sensitivity as (b)

Figure 19. Lightning Drive and Response Waveforms in -1B Specimen.

Second Lightning Exposure on -1B Specimen

The specimen was still in the test stand. It was decided to go to the full discharge capability of the test setup. This represented 150 kilovolts charge on the 0.54-microfarad capacitor bank, and a discharge peak current of approximately 48 kiloamperes through the bar across the surface of the specimen. A camera was arranged to photograph the specimen during the discharge, although the test area could not be darkened. Three people also observed the discharge.

The discharge took place without apparent damage. No one saw any flashing, but the camera shutter failed to open at the correct time. Therefore, it was decided to run one more 150 kilovolt discharge before the specimen was removed from the setup and arranged for Thermograph studies. The discharge took place without any observed or photographed flashes or sparking on the specimen.

Damage Assessment of -1B After Second Lightning Exposure Run

Visual assessment of the -1B specimen did not reveal any changes. Although, in retrospect, most attention was directed to the open area of the coating and particularly to the coating in the immediate area adjacent to where the 5/8-inch rod had passed over the surface. The bus bar region had been looked at, but not with the concentration devoted to the body of the coating.

Resistance measurements showed that the bus-to-bus resistance had increased about three times from its previous reading (see Table I).

Electric heating power was applied in preparation for the Thermograph test. About 20 minutes after the power had been applied, a spot developed that was hot to the touch. It was about 2-1/2 inches long and located in the upper right hand corner (as viewed during the Thermograph tests) adjacent to the bus bar. The acrylic sheet developed a slightly raised spot and evidence of bubbling underneath. About 5 minutes later, the

hot spot had cooled down. This caused suspicion. The power was shut down and a resistance check made. The result was an open circuit. The lightning induced current and the subsequent steady heating current had burned an open circuit in the bus-to-bus circuit. No meaningful Thermograph picture could be taken.

Careful visual inspection revealed a slightly discolored trace growing from the lower bus out into the coating surface and parallel to and about 2 inches from the bus. This trace was very faint.

The open circuit condition of the now defunct -1B specimen did not allow further testing in the manner that had been previously planned. However, it was decided to see how it would react in the P-static simulator. As hoped, the high voltage caused sparking in the internal voids in the coating caused by lightning and subsequent heating current.

Figure 20 is a photograph which shows a large oak tree discharge as well as sparking along the right and left edges adjacent to the bus bars. The bus bars are the straight vertical lines bordering the open area of the transparency. Note the forked line in the lower right corner. (This corresponds to the lower left during the Thermovision tests.) The area that was hot to the touch and bubbled during the post-exposure heating is at the lower left edge in Figure 20.

After this P-static discharge exposure the damage was very visible. The action of the internal sparking had caused the flaws in the coating and in the bus-coating interface to be colored a faint pink. Examinations of the specimen before and after this P-static exposure indicated that the static discharge did not significantly increase the extent of the previous damage, but caused a visual enhancement of the existing damage. Attempts to photograph this damage were not too successful. Figure 21 is a photograph of the lower left edge of Figure 20 as viewed from the opposite side of the specimen. The bus bar is the solid line about 0.3-inch wide along the lower part of the photo.

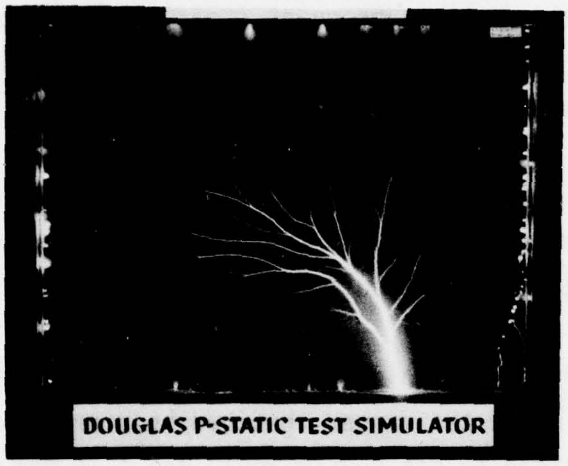


Figure 20. -1B Specimen Undergoing Static Discharge After Lightning Exposure.

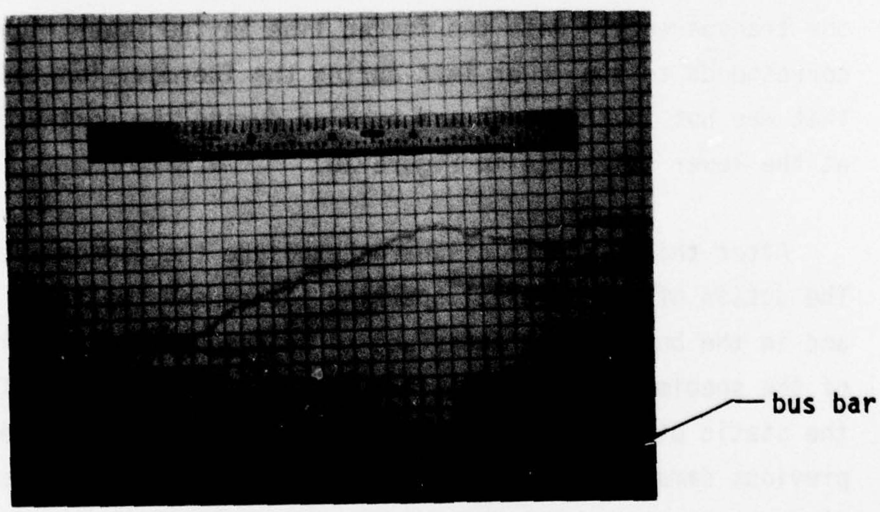


Figure 21. Static Enhanced View of Lightning Damage to -1B.

First Lightning Exposure Run on the -505B Specimen

The usual initial resistance and Thermovision measurements were run on the -505B specimen. The 5/8-inch rod that conducts the lightning current was placed over the deletion line of the specimen, and one-half of the resistive coating was instrumented with a current probe, as described in Section II, Page 14. Because of the total failure of -1B specimen, a more cautious approach was undertaken in the testing of the -505B specimen. The first lightning exposure consisted of four discharges from the 0.54-microfarad capacitor bank that had been charged to 25 kilovolts. The specimen was then removed from the lightning test jig and remounted for Thermovision inspection.

Damage Assessment of -505B After First Lightning Exposure Run

Resistance measurements (Table 1B) showed no significant change. Visual inspection also showed no change. The thermograph tests showed no significant change. Traces of the thermograph isothermal lines for the whole series of lightning exposure runs on the -505B specimen are shown in Figure 22. The specimen was returned to the lightning test jig.

Second Lightning Exposure Run of the -505B Specimen

The specimen connection and location of the lightning current bar were the same as in the first run. Five, 25 KV instrumentation discharges were made, and then one discharge of 75 KV.

Damage Assessment of -505B After Second Lightning Exposure Run

Resistance measurements (Table 1) showed no significant change. Visual inspection showed no damage or change. Visual inspection under polarized light (as described in Section II, Page 17), was first tried at this time. About 40 small (1/32-inch diameter) star-like bright spots were seen. The dots were spread rather uniformly under the surface and were not associated with the coating - bus interface. It could not be determined where, within the inner portion of the specimen, the spots were located, but, judging from

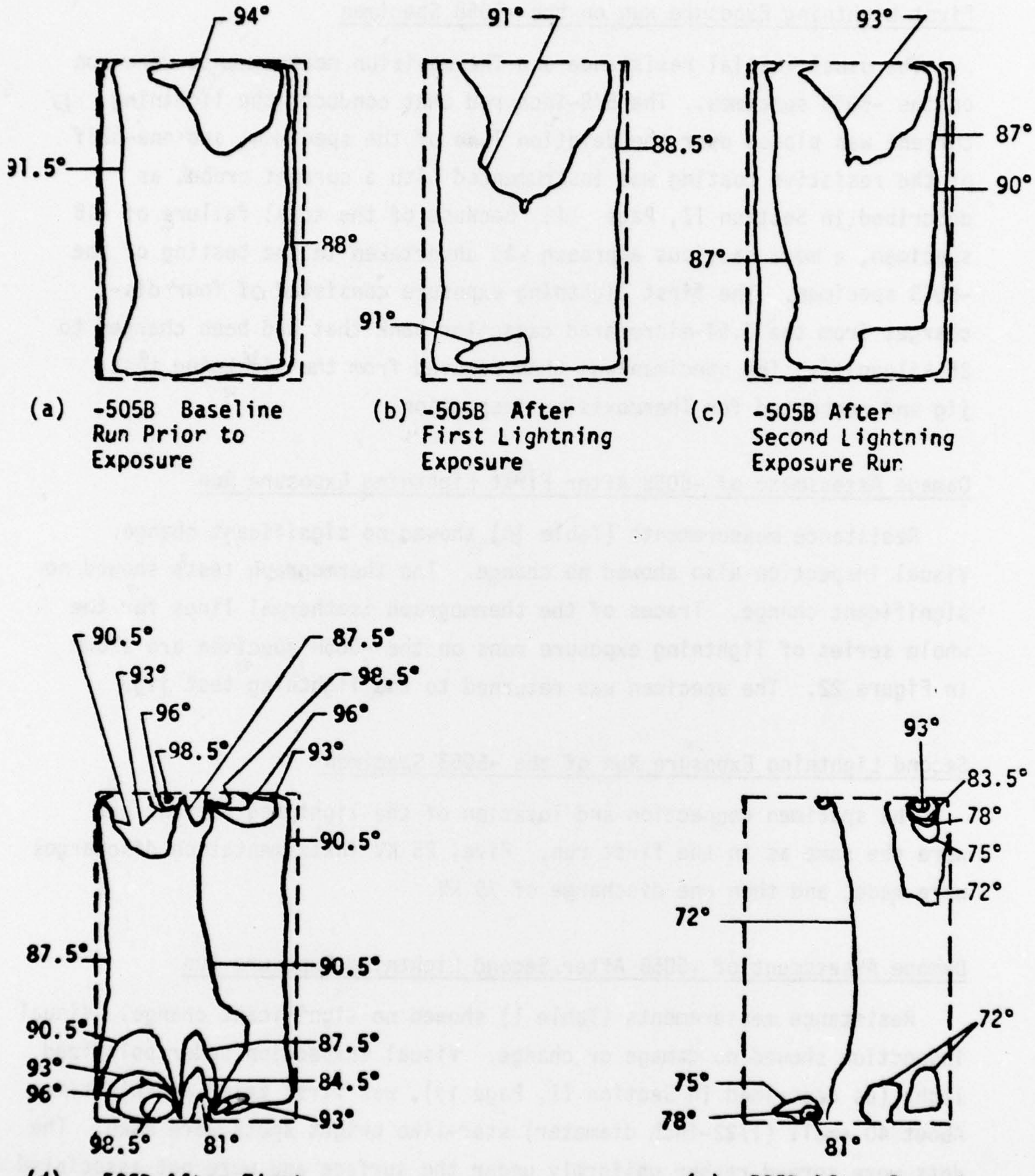


Figure 22. Isothermal Traces on -505B After Lightning Exposure.

the degree of paralax observed, the spots were probably not in the resistive coating. These spots could not be seen in unpolarized (normal) light. Their number and intensity did not seem to change as the specimen heated.

The Thermovision inspection of the specimen did not show any unusual changes in the temperature distribution.

The specimen was returned to the lightning test jig.

Third Lightning Exposure of the -505B Specimen

Only one discharge was made during this run. It was made with 150 kilovolts charge on the 0.54-microfarad capacitor bank. The response waveform was recorded and was essentially the same as that of Figure 19d, except for the amplitude.

Damage Assessment of -505B After Third Lightning Exposure Run

Resistance measurements showed that the upper coating segment had increased from 38.5 ohms to 41.4 ohms. The lower portion, which was instrumented with the Stoddart current probe, had only increased slightly from 38.1 ohms to 39.0 ohms. The direct grounding of the upper coating buses at several places produced a lower impedance total current path than did the path through the lower segment which had only a single wire interconnecting the two buses. Since the drive excitation was symmetrical for both coating segments due to the central placement of the 5/8-inch rod, the lower impedance path undoubtedly had the larger current. The peak current in the lower, instrumented segment was approximately 130 amperes.

Visual inspection of the specimen showed some burning of the buses and nearby gold coating for about 2 inches on each side of the deletion line for all four bus segments. There was no noticeable change in the gold coating anywhere else. No sparking was noticed during the discharge.

Figure 23a is a photograph of a segment of the bus where no burning occurred. Figure 23b is a similar photograph at the deletion line showing the damage to the bus-gold coating interface. The background grid is 0.2-inch square. The two segments of the bus can be seen. The current probe was in the circuit of the bus on the right in Figure 23b. This type of bus-gold coating damage was not seen in the -1B specimen. The Thermovision inspection showed a decided change in the temperature distribution around the previously identified areas of bus damage. Figure 22d shows an isothermal trace taken from the Thermovision color pictures.

Fourth Lightning Exposure Run of the -505B Specimen

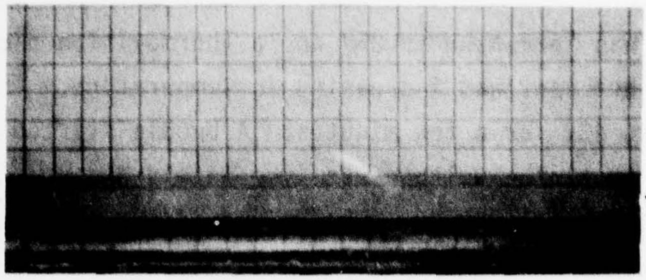
For this run the 5/8-inch bar, which carried the lightning drive current, was relocated over the center of the lower (instrumented portion) of the specimen as shown in Figure 6 and previously discussed in Section II. A single preliminary 25 kilovolt shot was fired, followed by a single 150 kilovolt discharge. The response waveform for the 150-kilovolt shot was essentially the same as previously seen (Figure 19d) except the peak amplitude was now about 150 amperes.

Damage Assessment of -505B After Fourth Lightning Exposure Run

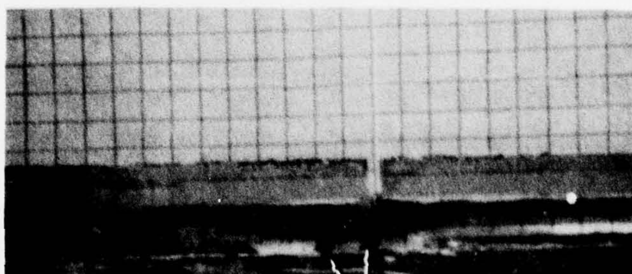
Visual inspection showed that this shot had further damaged the buses which connected to the gold coating segment under the excitation rod. One bus was damaged for nearly its full length, while the opposite bus had only minor additional burning under the excitation rod.

Resistance measurements (Table 1) showed only a minor (1 ohm) increase in the upper coating, which was farthest from the excitation rod. The lower, fully excited coating showed a significant resistance increase from 39 ohms to 54.5 ohms.

The specimen was heated for about 15 minutes with only 15 volts bus-to-bus voltage applied. At this low heating level a warm spot was detected by the Thermovision in the upper right hand edge (as viewed from the acrylic side with the "UP" marking to the left). This was near the bus that showed



(a) Photo of undamaged coating/bus interface area.



(b) Photo showing damage to coating/bus interface.

(Background grid is 0.2-inch on a side)

Figure 23. Damage to -505B After First 150 Kv Discharge.

the most damage in the visual check. A warm spot also appeared in the lower left side a few inches up and about centered in the right coating.

The voltage was increased to 25V and a Thermovision picture was taken. The upper right hot spot was increasing in temperature. The voltage was then increased to 43V for a few minutes. A bubble started to form in the upper right hot spot, the voltage was immediately dropped to 25V in order to prevent further damage. The Thermovision indicated a very hot spot which was well above the calibrated range for the Thermovision. Assessment was stopped at this time since it was evident that the specimen would self-destruct if full voltage were applied, as might be the case if this were an actual aircraft installation.

SECTION IV
CONCLUSIONS

CRITIQUE OF THE TEST METHODS

Static Electric Discharge Tests

The method used to apply the static charging to the specimen differs from the natural triboelectric charging process of rubbing ice crystals across the windshield surface. However, the experience gained from these current experiments, prior IRAD work, and the work reported in Reference 1 indicate that the static charging method used here produces very useful and representative results. The measurements of the discharge current in the conductive coating are believed valid, but much better and more easily attained measurements could be made if the test setup were fully shielded. The additional cost was not warranted for this test since the measurement of these signals was not the main objective of the tests.

Swept Stroke Lightning Tests

As noted in Section II, any laboratory simulation of lightning is a compromise, due first to a lack of detailed knowledge of the actual natural pheonomena, and second due to the limitations of laboratory equipment. For the specific tests reported here, the compromises do not degrade the significance of the technical conclusions. One major difference between the test and natural lightning is the use of a damped oscillatory wave excitation rather than a unipotential pulse. The laboratory damped wave could be made highly damped to produce a unipolar pulse. This was done during the setup phase of the work. The disadvantage of this approach was a greatly reduced peak current. The results showed that low level excitation does not have a noticeable damaging effect on the specimen. Therefore, a compromise was accepted to greatly reduce the damping factor to allow the peak current to rise to a higher level. The energy delivered to the resistive coating by the lightly damped curve is contained in several cycles of oscillation rather

than in a single unipolar pulse. Therefore, while the initial peak current discharge limit of this setup was only about 48 kiloamperes, as compared to a maximum probable natural lightning re-strike environment of 100 kiloamperes, the energy in the subsequent ring-down of the oscillatory wave raises the actual delivered energy in a few tens of microseconds to a more realistic maximum level. One should also recognize that a 100 kiloampere restrike will occur in less than 1 percent of the lightning flashes (Reference 2).

Since the general trend of damage possibility was the goal of this work, precise levels of current and energy were not required, and the compromises were acceptable.

Damage Assessment Techniques

The major damage assessment methods; visual inspection, electrical resistance, and Thermovision mapping, were considered to be quite adequate for the desired goal. The Thermovision equipment is expensive and would have been unjustified for a program of this funding level had it not been available. The real-time, visual presentation was far more valuable than might be indicated by the recorded data. The test personnel were able to gain a high degree of understanding of what was happening by the use of this equipment. If more time had been available, it is believed that more precise adjustments might have permitted an easier interpretation of the photographed records. However, the data as recorded were adequate.

ANALYSIS OF THE TEST RESULTS

Static Electric Discharge Effects

These tests indicate that for a windshield or canopy of moderately large size, as used in these tests, a lifetime of surface discharging induced transients should not have a significant impact on the integrity of an anti-icing or RCS conductive coating, provided that the initial coating and bus design and manufactured product were free from flaws.

If flaws were present, they might remain undetected in an unheated design until in-service exposure to a static electric environment might enhance the flaw visibility to an unacceptable level.

The small changes in the -1A specimen, noted after the static electric exposure, were only an enhancement of the anomalies already present. It may be possible that many cycles of heating and cooling, without benefit of the discharge transients, might have brought about a similar change, although this supposition was not proved by this test program, nor would this be the case for an unheated RCS coating. It may also be possible that moisture encroachment into the edge area of a windshield or canopy, where most buses are located, would combine with heat cycling and heater voltage stress to create a situation where the presence of static discharge induced transients might trigger a failure that might not occur otherwise if the discharge transients were not present. This possibility, too, is not derived directly from these tests, since the program was not planned to be this all-inclusive.

Swept Stroke Lightning Effects

Swept stroke lightning that passes over the surface of a windshield or canopy and produces a high level re-strike to the windshield or canopy will be a fairly rare occurrence. However, if it does happen, these tests indicate that one may reasonably expect damage to the conductive coating system.

The previous swept stroke tests documented in Reference 1 and summarized in Item 11, Page 101, of that reference identified induced currents of 3000 amperes in the simulated windshield heating coating for a non-attaching restrike current of 79 kiloamperes. Data from this present series of tests were obtained by a different test method using specimens which had real heating coatings, and produced induced currents considerably below those of the Reference 1 test series. For example, the present tests on the -1B specimen, with a generator charge of 150 kilovolts, produced a discharge of 48 kiloamperes through the bar across the specimen surface.

The induced current in the conductive coating was beyond the measurement limits of the equipment, but extrapolates to 245 amperes, on the basis of the actual measured values of Figure 19.

The gross differences in the induced current of the present tests and the tests of Reference 1 are explained by the fact that the simulated conductive coating of Reference 1, which was aluminum foil, had much lower resistance than the real gold coating. The gold coating for the -1B specimen had a bus to bus resistance of approximately 22 ohms and a resistivity of between 15 and 20 ohms per square. The resistance of the aluminum foil simulated coating was mainly in the joints between the foil segments. The resistance of the real conductive coating acts as a current limiter. Yet, in spite of the drastically reduced current in the real coating, damage did take place due to the induced current.

The most significant observation was that the noted damage did not take place in the main body of the coating. Rather, the damage was mainly confined to the coating-bus interface area. This type of failure is not unique to windshields of this type of construction or to products of this specimen manufacturer. Similar incidences of bus coating failure have occurred on other types of construction made by other companies. The main message of the damage assessment is that the subject of bus-coating interfaces probably needs much more attention from the standpoints of initial design and production quality control. If this area could be substantially improved, the service life of many windshields and canopies might be extended significantly.

SECTION V
SUMMARY AND RECOMMENDATIONS

SUMMARY

These tests and observations made during this program, including the work reported in Reference 1, indicate that static electric surface discharges occurring over the lifetime of a transparency having adequate thickness and dielectric qualities to prevent puncture should not directly introduce failures in the under surface resistive coatings of properly designed and manufactured windshields or canopies. On the other hand, swept stroke lightning with high level re-strike to the windshield or canopy may result in damage to parts made by today's standards. Improvements in the coating-bus interface design and manufacture hold promise for substantially reducing this damage.

RECOMMENDATIONS

The following are recommendations suggested by the work of the program:

1. Design and manufacturing research should be devoted to improving the bus-coating interface region. A possible source for guidance might be the thin film resistor industry where thin metallic films are joined to terminating electrical conductors. Many millions of these devices have been made and some have been susceptible to burnout from electrical transients.

2. Where production quantities justify the initial cost, the Thermovision method might prove helpful as a development and manufacturing quality control tool. Large maintenance depots might also benefit from this inspection technique.

3. A pre-delivery inspection, using a static discharge technique, might detect coating weaknesses that less sophisticated thermal measurements might miss. This is particularly applicable to coatings which are not designed to be heated electrically, such as RCS coatin

4. The failure-prone edge areas of windshields should be studied more thoroughly to evolve design and manufacturing methods which will produce longer life parts. All environments, such as pressure changes, temperature changes, moisture, solar radiation, lightning and P-static discharges should be included.

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